THE HEAT WAVE FROM THE INTERMOUNTAIN AREA TO THE NORTHERN GREAT LAKES, JUNE 9–13, 1956

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1. INTRODUCTION

The average temperature of June 1956 was much above normal in the northern Plains region and normal or above from the southern Plateau region eastward to the Upper Great Lakes region. It was in the northern and central Plains region where the greatest departure from the monthly normal occurred, reaching a plus 9° F., at Rapid City, S. Dak. (Chart I-B). One of the principal factors contributing to this large departure of temperature was the heat wave of June 9–13, 1956, which extended from the interior of the Plateau region of the West into the Upper Great Lakes region. During this period of five days few monthly maximum temperatures were exceeded but numerous high readings for the day were equaled or new records established in the Northern Plains and Upper Mississippi Valley. The area of high temperature with which we are primarily concerned will be found within the plus 10° F. anomaly line (fig. 4B).

This heat wave was the first hot spell of the summer season and although not of long duration it presented several interesting facets for study. The development of the upper ridge that attended the heat wave furnished a rather good illustration of dispersion of energy downstream. This energy had great concentration just south of the western Aleutians early in June. Also, in conjunction with the dispersion of energy, there occurred a rapid cyclogenesis over the Gulf of Alaska and intensification of the trough off the western coast of the United States.

2. ANTECEDENT CONDITIONS

A deepening surface wave west of Japan on June 1 moved rapidly north-northeastward concomitant with a deepening 500-mb. trough moving eastward off the coast of Kamchatka. By the afternoon of the 2d, Greenwich time, the surface and 500-mb Low centers were in the vicinity of Adak, Alaska with central values of 960 mb. and 17,000 ft. respectively. During this same time the strong cold Low, both surface and aloft, near weather ship "Papa", 50° N. and 145° W., was being forced eastward toward Canada in a readjustment of wavelengths. Associated with these occurrences the Adak Low was transporting warm air northward over Alaska and developing, both at the surface and aloft, a short-lived but large-amplitude ridge over the central Pacific Ocean. By the morning of the 4th (fig. 1A) the eastward movement of the cold Low and trough off the west coast of North America was being retarded by the continued maintenance at all levels of a strong ridge over central United States. Concurrently a short-wave trough began moving out of the long-wave position near Adak, Alaska and into the stream of strong westerlies that were transporting cold air rapidly eastward. Between the afternoon of the 4th and the morning of the 5th the short-wave trough damped the Pacific ridge, and a belt of strong westerlies then prevailed from 180° long. to the west coast of the United States as the cold Low and trough along the coast had weakened and moved inland. This strong flow of westerlies prevailed through the 6th, but by 0300 GMT of the 7th slight cyclonic curvature had begun to develop near 150° W. (fig. 1B). This area of increased cyclonic vorticity continued to develop through the 1500 GMT chart of June 7. But changes of spectacular proportions were occurring prior to this time in the north central Pacific Ocean indicating that a definite readjustment was underway in the large-scale features of the circulation and that the strong westerlies would soon break down and the Pacific circulation would return to a more meridional flow.

This development occurred amain between the 5th and 6th in the formation of a pronounced ridge in the Adak area where previously the intense Low center had been located. This change at 500 mb. amounted to a 700-ft. rise of height in 12 hours, slightly in excess of 1,000 ft. in 24 hours, and 1,900 ft. in 84 hours. The 500-mb. height change chart for the 72-hour period ending at 0300 GMT of June 6 (fig. 1A), illustrates the magnitude of the tremendous energy involved in this development. During the 6th and 7th the long-wave trough off the west coast began to reintensify as the short-wave trough from the Aleutians approached the long-wave trough position. However, the principal intensification of the trough off the west coast, both at the surface and aloft, and the subsequent intensification of the pressure ridges over the central Pacific

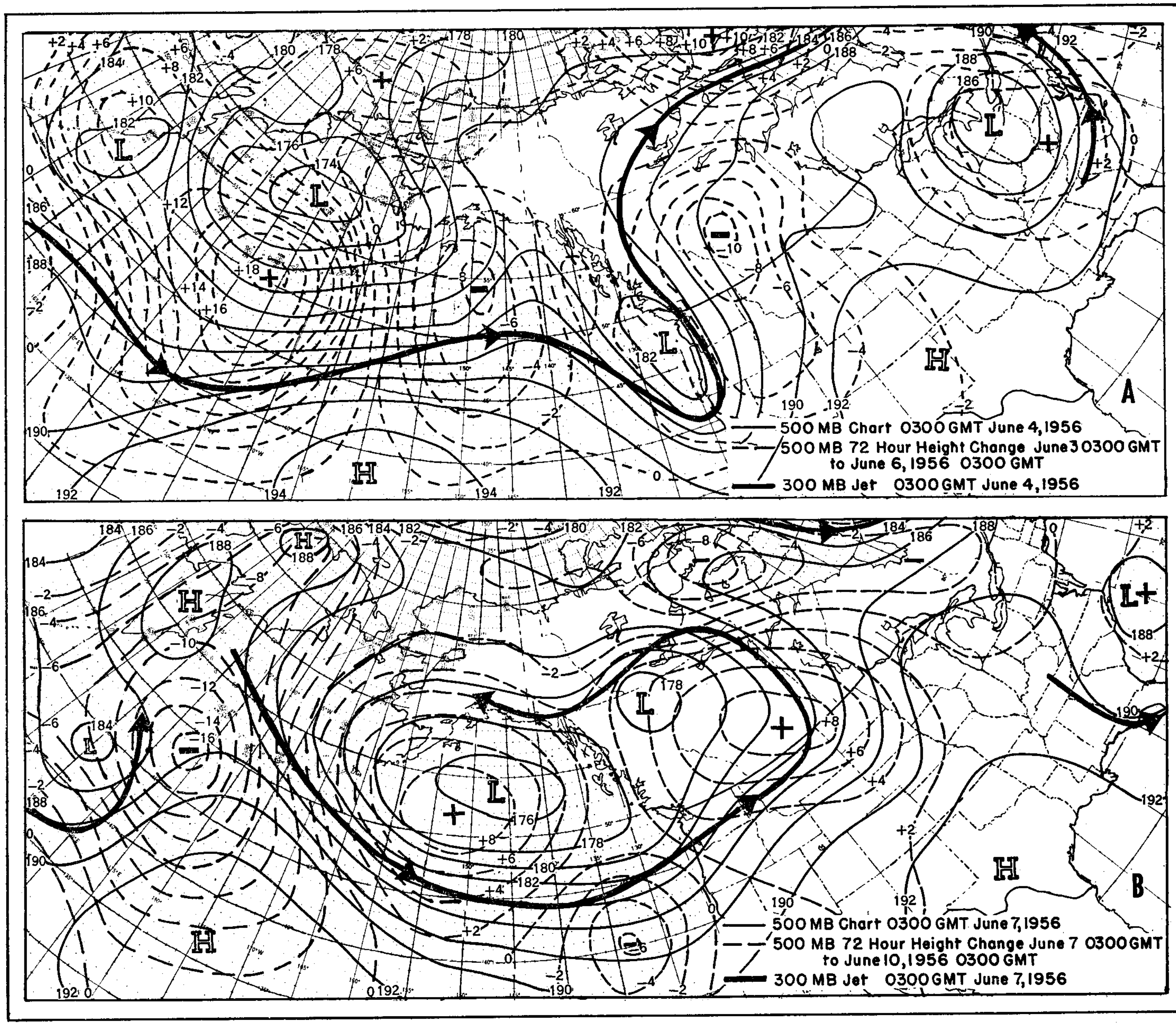

FIGURE 1.—(A) 500-mb. contours (solid lines) 0300 GMT, June 4, 1956 with height values in hundreds of feet. 300-mb. jet stream 0300 GMT, June 4 is indicated by heavy line with attendant arrows showing direction of flow. 72-hour 500-mb. height change for period 0300 GMT June 3 to 0300 GMT June 6 inclusive is shown by dashed lines. Height change values are in hundreds of feet with rise and fall areas indicated by plus or minus signs. (B) 500-mb. contours (solid) and 300-mb. jet stream for 0300 GMT, June 7, 1956. 72-hour 500-mb. height change (dashed) is for period 0300 GMT, June 7 to 0300 GMT, June 10, 1956 inclusive.

and the United States can be attributed in part to barotropic energy dispersion from the Pacific. Further discussion of this detail will be given in section 4 of this paper.

By afternoon on the 6th (GMT) several flat weak waves appeared on the east-west surface front extending across the Pacific Ocean. The front was in juxtaposition with both the strong westerly flow at 500 mb. and the 300-mb. jet stream. But it was the afternoon of the 7th before one of these waves indicated definite development as it began moving through the long-wave trough. That conditions were favorable for this wave to develop was clearly indicated by its proximity to a maximum of cyclonic vorticity on the 500-mb. chart. Strong cyclogenesis in the region of 45° N., 147° W. was also indicated on the Fjørtoft vorticity chart for 1500 GMT of the 7th. At the surface a well-defined temperature gradient existed across the front. Also, large 500-mb. height falls were moving into the area and these falls had increased to 800 feet during the 24 hours ending at 0300 GMT of the 8th. The development of this Low aided materially in the southward transport of cold air aloft off the central California coast and in the sharpening of the resulting trough. Later it was this front that brought cooler air in from the west and northwest to end the heat wave.

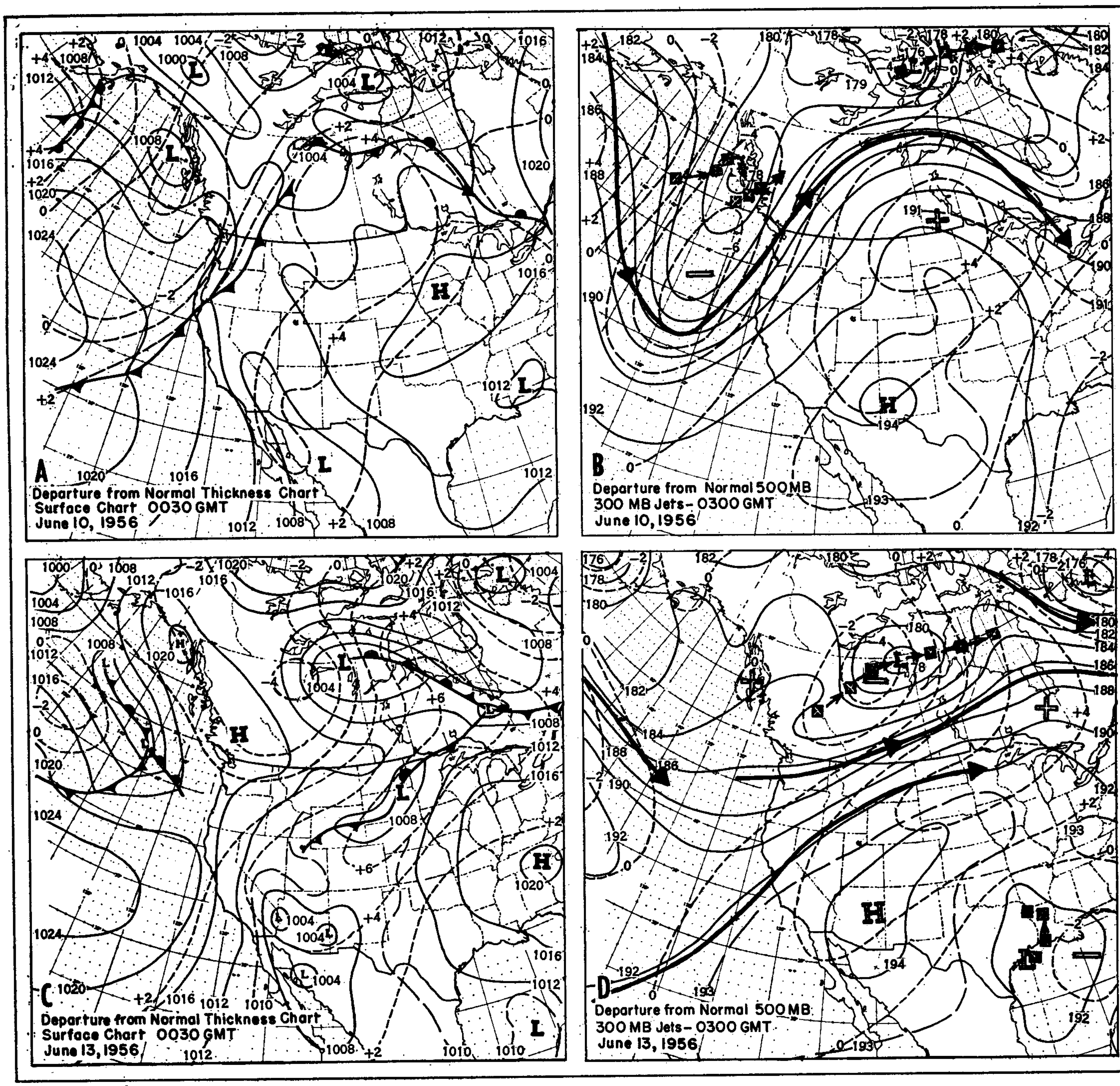

FIGURE 2.—(A) Sea level pressure pattern (solid lines) with fronts 0030 GMT and 1000–500-mb. thickness departure from normal (dashed lines labeled in hundreds of feet) for 0300 GMT, June 10, 1956. (B) 500-mb. pattern (solid lines labeled in hundreds of feet); 500-mb. departure from normal height (dashed lines labeled in hundreds of feet); and 300-mb. jet streams (heavy black line with arrows indicating direction of movement) all for 0300 GMT, June 10, 1956. 12-hourly center positions indicated for 36 hours prior to and after time of chart. (C) Same as (A) for June 13, 1956. (D) Same as (B) for 0300 GMT, June 13, 1956.

3. SYNOPTIC CONDITIONS, JUNE 9–13, 1956

By early morning of the 9th a flat high pressure system of 1019 mb. had become practically stationary over central Iowa. And during the previous 24 hours the cold front that had extended southwestward from the Low in the Moosenee, Ont., area dissipated as the Low weakened and moved southeastward. Simultaneously an occluded front moved onshore from British Columbia to northern Oregon, but the previously attendant Low center remained in the trough off the west coast. Indications of a building ridge were present in the vicinity of the Washington coast while in the extreme Southwestern States the heat Low persisted and extended into Mexico.

The upper air picture as reflected in the 500-mb. chart continued to show the 19,400-ft. contour over New Mexico and southward into Mexico. However, during the past day the 500-mb. heights had increased to the north of the center, building a weak ridge over the Intermountain and Plains Region with the 19,200-ft. contour approaching the Canadian Border near the Montana-North Dakota line. This building was in conjunction with the southward extension and sharpening of the upper trough off the west coast. Simultaneously, the Low associated with this trough had moved 450 miles northeastward and weakened slightly. These changes produced a tightening of the pressure gradient over Vancouver Island and the Pacific Northwest, thus increasing the speed of the wind. Furthermore, it produced a backing of the wind to a more southwesterly flow resulting in the advection of warm air farther north. Tatoosh Island, Wash., was reporting a wind of 85 knots from 220° at this time at the 500-mb. level.

On the 10th (fig. 2A), the 0030 GMT surface chart was practically unchanged from that of the preceding day as to intensity and position of the pressure centers and fronts over the central and western portions of the nation. In Canada a weak Low was developing near Fort Smith, N. W. T., with the western occluded front moving into its center. Off the west coast a building anticyclone was moving toward the mainland and was displacing the weakening cyclone northward to a position due west of Annette Island, Alaska.

Aloft the 500-mb. chart (fig. 2B) also indicated a minimum of change in the position and intensity of the anticyclone center above southern New Mexico and of the cyclone center northwest of Vancouver Island and over the Queen Charlotte Islands. However, there had been a definite increase during the past 24 hours in the amplitude of the ridge above the Plains region and the Provinces of Alberta and Saskatchewan as well as a sharpening of the trough off the west coast. The Pas, Man., had recorded a height rise of 800 feet and a temperature rise of 12° C. during the past 48 hours at the 500-mb. level. Concurrently with this change, a fall of 600 feet in height and a temperature decrease of 13° C. had occurred in the trough near 40° N., 133° W. Winds had continued to back over the West Coast States and were now flowing from 180° to 200° with continued high speed.

By 0030 GMT of the 11th the surface chart indicated rising pressures over the Southeastern States as the subtropical High extended westward into the area. A weak High continued to be maintained over extreme southeastern Iowa or west central Illinois. Pressure gradient was quite flat over the eastern half of the country but increasing gradation was occurring over the western portion of the nation. This gradient intensification was most pronounced along the Pacific Coast States due in part to the troughing that was occurring southward along the occluded front and also to the eastward building of the high pressure cell west of the front. Surface pressures in the western portions of Washington and Oregon had risen 4 to 10 mb. during the past 24 hours. The Low attendant on the western front had a central value of 1002 mb., in the vicinity of Edmonton, Alta. And the front had moved to just east of the Idaho-Montana northern border, then streched southward entering Nevada in the extreme northwestern corner and leaving the coast near Santa Maria, Calif.

That the surface front extended into and across California at this time was well substantiated by approximately 1,200 ft. of thickness gradient to the rear of the front on the 1000–500-mb. thickness charts for 1500 GMT of the 10th and 0300 GMT of the 11th. That this amount was considerably above the normal June thickness in the California area was clearly illustrated by the 24-hour departure from normal thickness chart. A deviation of some 800 ft. occurred in less than 5° of longitude over northern California.[1]

The 0300 GMT 500-mb. chart for the 11th indicated a definite recession in the southern portion of the trough off the west coast. This produced a slight weakening of the central trough value in the vicinity of the Queen Charlotte Islands, while a new Low was forming over northwestern Washington. Above the States of Arizona and New Mexico the 19,400-ft. height line continued to be maintained. Advection of warm air aloft extended the crest of the anticyclone farther northward over south central Canada concomitant with its slow eastward drift. Over the southwestern sector of the Atlantic a continued westward advance of the subtropical ridge was maintained.

By 0030 GMT of the 12th the pressure gradient increase at the surface had persisted over much of the country as the western periphery of the extensive Azores High moved inland over several of the Southeastern States. Simultaneously with this occurrence the High over Iowa dissipated as the Canadian High previously near Moosenee, Ont., dropped southward to the Washington, D. C., area. In the Northwestern States, sea level pressures continued to rise as the trough moved eastward and a 1025-mb. High formed near Tatoosh Island, Wash. The Low previously near Edmonton, Alta., shifted northward to the Fort Smith, N. W. T. area and deepened. At the same time a new Low was in the process of development over the northern portion of Lake Winnipeg with the cold front extended from this Low to near Bismarck, N. Dak., then curved southwestward across Lander, Wyo., to Ely, Nev. with frontolysis occurring southwest of this station. Over the Southwestern States and Mexico the thermal Low persisted. The only new development indicated on the chart in this area was the formation of a weak Low over the Yucatan Peninsula.

In the upper air picture at 500 mb. the trough remained

[1] Due to the normal thickness gradient that prevails and frequently produces southerly thermal winds in excess of 50 knots over portions of California during the summer months when frontal structures may or may not be present, a slightly amended criterion for the placement of fronts in California has been developed. NWAC has recently developed an objective technique for use with the problems of frontal analysis in the California area. Objective study has shown that only when a distinct departure from normal thickness is indicated should fronts be carried across the southern and central portions of the State. At the present time this criterion is used by NWAC in determining occurrence of fronts in California.

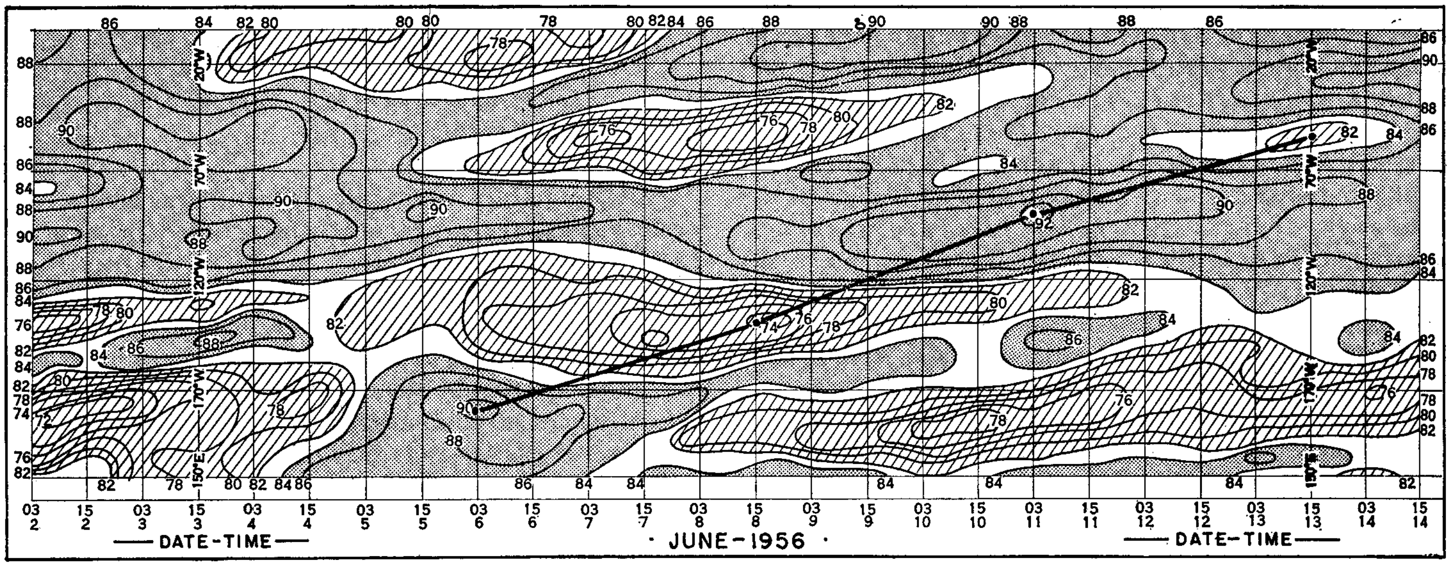

FIGURE 3.—Hovmöller diagram presenting a cross-section view of the 500-mb. constant pressure chart at 50° N. and extending from 150° E. to 5° W. during the period 0300 GMT, June 2, to 1500 GMT, June 14, 1956. Height values are in hundreds of feet but with the digit representing 10,000 omitted. The ridge areas are illustrated by stippling and the troughs by hatching. The heavy black line connecting alternate ridge and trough centers represents the trajectory of the dispersion of energy downstream.

along 131° W. but with weakening pressure gradient. An intensifying Low had moved over Alberta from Washington State during the past 24 hours with a central height value slightly under 18,000 feet. This development was moving eastward in the wake of the northern portion of the long-wave ridge over Canada and northern United States. Concurrent with these developments the subtropical ridge from the Atlantic joined with the ridge from the Southwestern States. And an upper Low attending an easterly wave began to intensify over the north-central portion of the Gulf of Mexico and the southern Mississippi Valley region.

In the early morning hours of the 13th (GMT) the surface chart (fig. 2C) presented a changing picture with the Low north of Lake Winnipeg weakening slightly as a deepening Low moved toward the Washington coast. The front associated with the old Low extended from International Falls, Minn., west-southwestward to the Great Salt Lake region. High pressure over the East was receding as the anticyclone near Washington, D. C., dropped south-southeastward and was located approximately 300 miles east of Jacksonville, Fla. The tropical Low from the Yucatan Peninsula had recurved and was moving northward toward New Orleans, La.

Deepening was occurring in the Low north of Lake Winnipeg on the 0300 GMT 500-mb. chart of June 13 (fig. 2D) as a strong westerly flow was damping the long-wave ridge from the James Bay region of Canada to the Great Lakes. The pivot point of the ridge line continued to be maintained over western Colorado. Over Illinois the northward movement of the trough from the Gulf of Mexico produced a separation of the Atlantic and the Continental ridges, while off the west coast the long-wave trough had practically disappeared.

Strong high pressure over western Canada was pushing southward to the rear of the old Low that had begun moving eastward across Hudson Bay during the 24 hours preceding the 0030 GMT chart of the 14th. By this time the surface front extended from Sault Ste. Marie, Mich., to Denver, Colo. High pressure over the East continued to weaken and yield ground to the deepening cyclones over the Western States and also off the Pacific Coast. In the States of Louisiana and Mississippi a weak tropical Low had moved north of New Orleans, La., spreading cloudiness and precipitation over a considerable area.

In the upper air, southern Canada was under a rather strong westerly flow by 0300 GMT of the 14th, while concomitantly the Arizona-New Mexico ridge was withdrawing southwestward from the Central States and the Atlantic subtropical High had receded to the southeastern coastal States. The tropical storm center was moving northward over central Louisiana with 500-mb. heights slightly less than 19,000 ft. A well-developed cyclonic flow was prevalent within 400 miles radius of its center.

4. DISPERSION OF ENERGY

One factor contributing to the heat wave of June 9–13, 1956 was the barotropic dispersion of energy downstream in the mid-tropospheric long-wave pattern. As previously mentioned, 500-mb. heights rose tremendously in the central Pacific Ocean during the 3-day period ending 0300 GMT, June 6, with a maximum rise of 1,800 ft. noted in the central Aleutians (fig. 1A). These rises were associated with a building ridge which reached its maximum intensity near 180° long., on the morning of June 6. The initial source of the energy associated with the building of this ridge appears to have moved out of Siberia. The chain of events following the building of the ridge in the Central Pacific consisted of the deepening of the long-wave trough off the west coast of the United States (figs. 1B and 2B), the intensification of the ridge in the west central portion of the United States (fig. 2B), and the deepening of the Low near Newfoundland (fig. 2D). For a graphical picture the Hovmöller chart [1] provides a particularly good illustration of the dispersion of energy downstream (fig. 3). Note the regular interval of approximately 60 hours between the appearance of maximum amplitude development of alternate trough/ridge occurrence during the eastward progress of this energy.

Table 1 presents values of the observed speed of the dispersion of energy or "group velocity." A brief review of the concept of group velocity may be in order; Carlin [2] states, "If two sets of waves of slightly different wave length are traveling through a mediun and the velocity of the waves (phase velocity) is a function of the wave length, then one of the sets of waves will travel faster than the other . . . The velocity of the regions of reinforcement or interference is called the *group velocity* . . . The increase and subsequent decrease in wave amplitude is often observed to travel along a wave train at a rate much greater than the phase velocity of the wave, and it is this phenomenon which is believed to be directly associated with group velocity." Thus, the group velocity

TABLE 1.—*Time, place and intensity of maximum anomalies illustrating progressive intensification downstream*

A. Using 5-day mean 700-mb. charts

Date	Lat. ° N.	Long. ° W.	Maximum anomaly (ft.)	Distance between centers (mi.)	Rate of dispersion (knots)
June 6	42	170	+480		
				1,680	28
June 8	55	132	−340		
				1,550	32
June 11	47	93	+280		
				1,460	20
June 14	60	58	−170		

B. Using daily 500-mb. departure from normal centers of action

Time GMT	Date	Lat. ° N.	Long. ° W.	Maximum anomaly (ft.)	Distance between centers (mi.)	Rate of dispersion (knots)
0300	June 6	46	174	+800		
					1,550	25
1500	June 8	48	138	−1,000		
					1,700	28
0300	June 11	53	94	+600		
					1,360	23
1500	June 13	56	55	−400		

C. Using the Hovmöller chart along 50° N. Lat.

Time GMT	Date	Long.	Distance between centers (mi.)	Rate of dispersion (knots)
0300	June 6	180°		
			1,500	25
1500	June 8	140° W		
			1,900	32
0300	June 11	90° W		
			1,360	23
1500	June 13	55° W		

may be obtained by measuring the rate at which a maximum of amplitude travels through a wave train.

Table 1 portrays the concept of group velocity in a more quantitative fashion. It is composed of data obtained from three different sources which were selected to determine the observed rate of energy dispersion downstream.

Table 1 Part A is based on a series of overlapping 5-day mean charts prepared in the Extended Forecast Section showing the distribution of the departure from normal of 5-day mean 700-mb. height. The time and place where centers of positive and negative departures from normal attained their maximum intensity have been determined by interpolating among these charts. The rate of energy dispersion or group velocity results when the linear distance between centers is divided by the time interval between their occurrence.

Part B is based on the time and place where daily 500-mb. departure from normal centers of action reached their greatest intensity. Again, the linear distance between centers is divided by the time interval between their occurrence to obtain the group velocity.

Part C is based on the time and place of progressive amplification propagated downstream in the troughs and ridges represented by the Hovmöller chart (fig. 3). Group velocity is then obtained in the same manner as above.

Values obtained for group velocity were strikingly similar in all of the three methods used. From the ridge in the central Pacific to the trough off the west coast the rate of energy dispersion averaged 25 to 28 knots, while from the trough to the next ridge in the west central United States the average was 28 to 32 knots, and from this ridge to the next impulse, near Newfoundland, the average was 20 to 23 knots. These values seem consistent with studies made previously. Carlin [2] made a study of a winter case where the group velocity averaged near 40 knots. Klein [3] found in a summer month (August 1953) that these speeds averaged near 18 knots, or about half of the value obtained by Carlin. Since the rate of energy dispersion depends directly on the zonal index, smaller values in summer should be expected. In this case the values observed, being between those obtained by Carlin and Klein, would seem reasonable since June would normally have a lower zonal index than a winter month but probably not as low as the warmest months of July and August.

5. PLANETARY PATTERNS AND ANOMALIES FOR HEAT WAVES

There are several features of the planetary wave pattern that are known to be essential for the development and occurrence of a summer heat wave over the United States. Some of these features are: First, a long-wave trough of strong intensity and amplitude must be present for the transport of warm air northward. Second, there must be an almost simultaneous building or intensification of a long-wave ridge immediately east of the long-wave trough position. Third, the departure from normal heights in the long-wave troughs and ridges must be large. Fourth, stagnation of these features is essential for a long-period heat wave.

Previous articles by Klein [4], Winston [5], Hawkins [6], and Holland [7], have shown certain conditions to be necessary for the occurrence of much above normal summer temperatures over the United States. The location and intensity of the mean 700-mb. long-wave troughs and ridges were most important in determining the area of greatest surface deviations from normal. In most of the cases discussed by these authors the axis of positive departure from normal of the 700-mb. heights has been along an east-west or northeast-southwest direction over the United States with the maximum attendant temperature deviation having occurred along this axis. The associated long-wave trough negative anomalies have been inland over the extreme Western States. The result of this has been that most of the recent heat waves have prevailed over South Central and Eastern United States rather than over the North Central and Western States. In this regard a summary will show that during the past 10 years more than half of the Junes have shown above normal temperature averages for the month in most States east of the Intermountain Region and west of the Appalachian Mountains. The States within this area that did not conform to this pattern are Montana, North Dakota, and South Dakota, all located in the northern Plains region, where 6 or more of the last 10 Junes have been below their normal temperature. In the middle portion of the Mississippi Valley, Iowa and Illinois have had an equal number of warm and cold Junes during this 10-year period. Texas has had a preponderance of warmer than average Junes with a ratio of 8 to 2 for the past decade, while New Mexico, Oklahoma, Arkansas, Louisiana, and Mississippi have had 7 of the past Junes with above normal temperatures. Over the Eastern States the ratio has also been approximately 7 to 3 for above normal temperatures.

These areas in the United States that have experienced much above normal monthly temperatures during the month of June during recent years also have had a positive anomaly on the 700-mb. monthly mean chart ranging from nearly 100 to 200 feet. During the same years that excessive June heating occurred there has been an almost equally large negative anomaly along or over our west coast. This relationship between temperature and the circulation aloft has been quite well covered by Martin and Hawkins [8].

6. PLANETARY PATTERN AND ANOMALIES FOR JUNE 8–14, 1956

In the preceding article by Green [9], the ridge line on the 700-mb. mean height chart for the month of June, as well as the axis of the area of positive departure from normal of the 700-mb. mean chart, is in a more nearly north-south direction than in the cases previously mentioned. On the departure of average temperature from normal chart for June 1956, (Chart I–B) it can be seen that the axis of the maximum positive anomaly is parallel to but slightly west of this ridge line. Green [9] also has presented the mean 700-mb. chart for June 1–15 along with its anomaly, (his fig. 4A). Note that the ridge line and axis of greatest departure from normal on this chart are nearer to the axis of maximum temperature departure for June, as would be expected with the heat wave having occurred during the first half of the month. These charts also locate the long-wave trough position several degrees west of the Pacific Coastal States thus allowing the long-wave ridge pattern to be maintained farther west and so permitting the warm air with resultant high temperatures to flow over the Northern Plains and into central Canada. The 6° F. positive anomaly of the departure from normal temperature for June extended northward across central Saskatchewan, and the 4° F. positive anomaly extended into northeastern Alberta, to nearly 60° N.

With monthly anomalies indicating large deviations it must be expected that during a short-period heat wave daily charts would show considerably larger departures from normal. In order to make daily anomaly comparisons it is necessary to use the 500-mb. departure from normal charts. At this level the deviation approaches twice the 700-mb. value. The 700-mb. departure from normal chart for June 1956 (see preceding article by Green, fig. 1) had a positive anomaly ranging from 120 ft. near Salt Lake City, Utah, to 150 ft. near Duluth, Minn.

At 0300 GMT the 500-mb. height anomaly charts for June 8 and 9 indicated a negative value in excess of 800 ft. west of Vancouver Island and moving east-southeastward, with a growing positive area exceeding 200 ft. spreading over the Intermountain and Plains regions. By 0300 GMT June 10 the negative departure had changed from an east-west to a north-south elongation off the west coast and extended from 25° N. lat. across the North Pole. A central negative area in excess of 600 ft. was west of Oregon while the area of positive anomaly, now in excess of 400 ft. continued to spread over central North America (fig. 2B). During June 11 and 12 the negative anomaly area shrank in size, recurved, and moved northeastward into southwestern Canada but the central value continued in excess of 400 ft. Concomitantly the growth of the upper ridge and its slow eastward progression produced positive anomalies in excess of 600 ft. centered in an area north of International Falls, Minn., and west of Moosonee, Ont. On the 13th and 14th the area of negative departures, with central values continuing in excess of 400 ft., advanced east-northeastward into central Canada. The area of positive anomalies remained practically stationary but with central values decreasing to slightly above 400 ft. (fig. 2D). It was at this time that the ridge line obtained a more east-west orientation with the pivotal point continuing over Utah and Colorado as the heat wave was now spreading into the Northeastern States.

Generally during this period, the area of departure from the normal thickness (1000–500 mb.) was in close agreement with the 500-mb. height anomaly as to intensity and area. This would indicate that the surface pressures and the 1000-mb. height values were in close agreement with the normal values. The one exception of any note was on June 13 when a tropical storm moved into the New Orleans, La., area. At this time the 500-mb. anomaly chart had a negative area in that region while the 1000–500-mb. thickness anomaly chart remained unchanged. This would indicate that both surface pressure and 500-mb. heights were falling at a uniform rate.

As has previously been stated the area of high temperatures with which we have been concerned is the region where readings were 10° F. or more above the monthly normal maximum as shown by fig. 4B. It is interesting to note that the area of daily highest temperature for the period shown on fig. 4A is for the most part in rather good agreement with the axis of departure from normal of either the 500-mb. constant pressure or the 1000–500-mb. thickness chart. The approximate position of these ridge lines of the positive anomalies can be observed for the high temperatures of the 9th and 12th by reference to fig. 2A, B, C, D. Furthermore, these charts tend to illustrate that the pivotal point of the ridge line of the positive departures from normal occurred in the States of Utah, Nevada, and western Colorado indicating why the heat wave spread over the greater portion of the Northern States.

The same correlation between the ridge line of the positive anomalies and the high temperature carried throughout the entire heat wave. There was very little to choose from as to the position of the ridge line on the departure from normal of the 500-mb. chart or the 1000–500-mb. thickness chart. Temperatures of 10° F. or more above the monthly normal maxima almost invariably were associated, as would be expected, with values 200 ft. or more above the monthly normal for the 500-mb. height and the 1000–500-mb. thickness, thus indicating a good use for 500-mb. prognoses as an aid in the forecasting of maximum temperatures for the next day or two.

The jet stream during this period of hot weather was carried over Canada far to the north of its normal June position as may be observed on fig. 2B and fig. 6 of Green's preceding article. It was not until near the end of the heat wave that the jet returned to a more normal position. During this period the cyclonic developments were, as normally would be expected, carried well to the north of the United States and occurred to the left of the jet stream thus retarding cooling over the hot northern States and southern Canada.

7. ANOMALIES OF THE 500-MB. PROGNOSTIC CHARTS, JUNE 10–14

A comparison was made between the departure from normal heights of the actual 500-mb. charts and the NWAC 36-hour 500-mb. prognostic charts. The 0300 GMT charts were again selected for comparison as this was the upper air observation nearest to the maximum heat of the day.

Graphical subtraction using acetate overlays requires only a minute or two for obtaining the prognostic departure from normal for an area the size of facsimile section 1. The anomaly height chart of June 10 indicated that the 36-hour prognostic 500-mb. map had height values too low in the Northwestern States and because of this difference the prognostic positive anomaly ridge line was some 300 miles south and east of its actual position. Thus on this prognostic chart the probable occurrence of high temperatures was indicated east and south of the area where the high readings actually occurred.

By 0300 GMT of the 11th the prognostic departure from normal height chart for the 500-mb. level was in much closer agreement with the actual anomaly chart as to intensity and area covered as well as to the location of the ridge line. And on this prognosis the area of maximum temperatures in excess of 10° above the June normal maximum for each station was practically within the 200-ft. positive anomaly line.

The 0300 GMT height anomaly derived from the 500-mb. prognostic chart of the 12th again presented values much too low in the Western States but there was good agreement between prognostic and observed anomalies over south-central Canada and the Great Lakes region. From this chart it would have been difficult to foresee the band of high temperatures from near Elko, Nev., to Rapid City, S. Dak. However, the remaining area of high temperatures might have been expected.

The departure from normal prognostic charts on the 13th at 0300 GMT present about the same difficulties as encountered on the 12th: the tendency for too low height in the West favoring lower temperatures in the States of Nevada, Utah, and Wyoming than did occur. But in the north-central portion of the country there was excellent agreement between the prognostic ridge line and the area of high temperatures.

The prognostic departure from normal chart derived from the 36-hour 500-mb. prognosis for the 14th was in almost complete agreement over the United States and Canada with the actual 500-mb. height anomaly chart. Thus the area of expected maximum temperature was quite clearly defined.

It may be seen that, for the most part, the use of these prognostic charts could be of some aid in the forecasting of movements of maximum temperature areas. Generally these 500-mb. prognostic charts were normal to slightly below average in regard to accuracy according to NWAC verification system.

8. DISTRIBUTION OF MAXIMUM TEMPERATURES

The pattern produced by charting the date of occurrence of maximum temperature at each station during the period of June 9–13, 1956, is depicted by figure 4A. Date

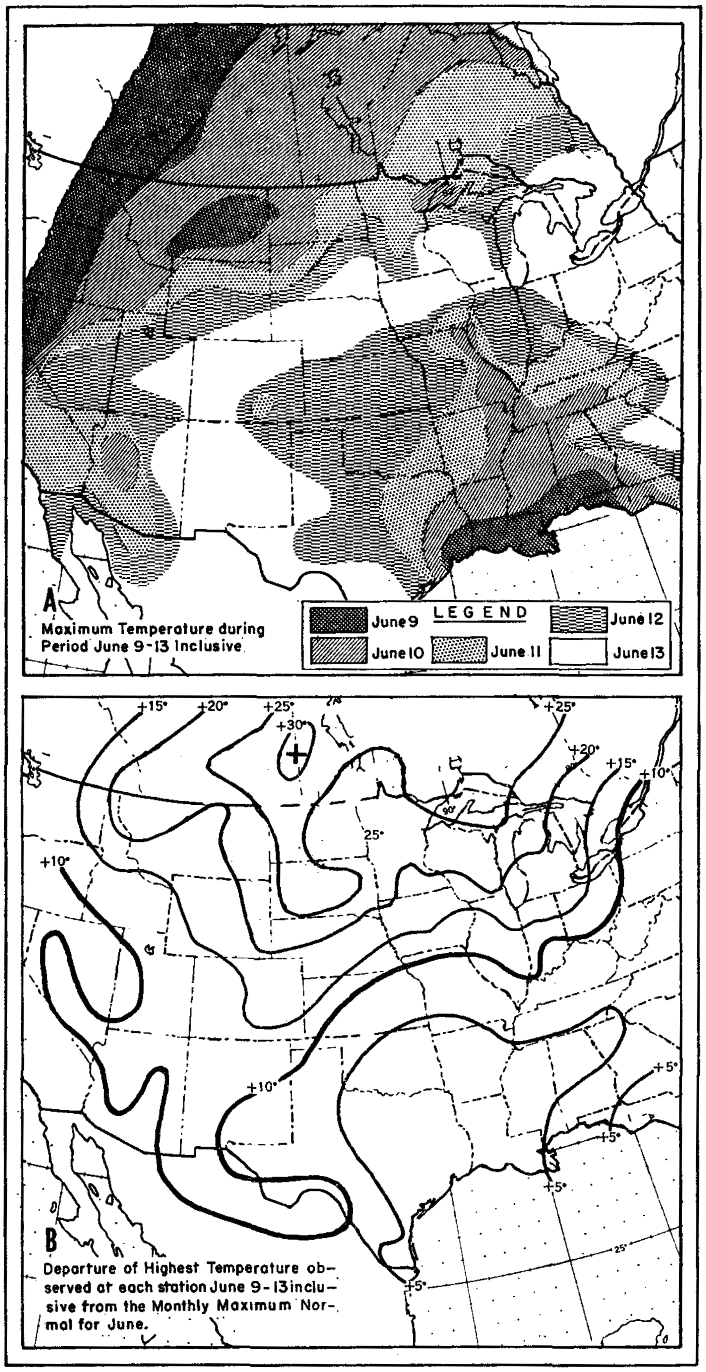

FIGURE 4.—(A) Date of maximum temperature occurrence during period of June 9–13 inclusive. Shading of different types has been used to distinguish different dates (see legend on chart). It is of interest to note the convergence of these dates bands of highest temperature into the white ribbon depicting the area of high temperatures on June 13, 1956 prior to the cooling that occurred on the 14th. (B) The departure of the highest temperature reported from June 9–13 inclusive from the maximum monthly normal at first order stations with lines of equal anomaly at intervals of +5° F. Maximum departures are found in the North Central States and southern Canada. The line of greatest departure, +10° F., encloses the heat wave area considered in this paper.

of occurrence of the highest temperatures during this period is indicated by the different shadings. On June 9 the highest readings were confined for the most part to the Northwestern States and the central Coastal States along the Gulf of Mexico. Each successive day the areas of maximum temperature advanced toward each other with the largest area of maximum temperature in the United States occurring on June 12. The chart shows quite clearly the gradual concentration of maximum temperatures by June 13 into a ribbon-like area extending from Mexico northward into southern Wyoming, then curving east-northeastward across the Plains into the Upper Great Lakes region before spreading fan-like over the central portion of eastern United States.

That the maximum temperatures occurred early in the period over the Northwestern States is easily understood from the synoptic situation. On June 10 (fig. 2A) a frontal system was oriented northeast-southwest across eastern Washington and central Oregon. Maximum temperatures were reported in advance of this front. Cloudiness and cooler air attended the slow but persistent eastward and southward movement of this front. Its passage brought an end to the high maximum readings. By 0030 GMT, June 13 (fig. 2C) the front had reached a position extending from International Falls, Minn. southwestward across central South Dakota and through central Wyoming.

The northward and westward spreading of afternoon high temperatures from the Gulf region is somewhat more difficult to explain. Charts at the 850-mb. level June 10 indicated a weak easterly wave moving slowly across the Gulf of Mexico and on June 11 this wave extended into the eastern Gulf States. Note the small surface Low centered in Alabama in figure 2A. Circulation was weak but easterly winds and cloudiness may have aided in keeping the area of highest temperature farther north and west. By the 12th and the 13th thickening cloudiness and precipitation from a small tropical storm moving northward through the central Gulf of Mexico kept temperatures relatively low throughout the central Gulf States.

Actual values of maximum temperatures that occurred during this period have not been published with this article for two reasons: First, few monthly or yearly extreme values were equalled or exceeded at first-order stations, and second, it was thought that the departure from normal of the monthly maximum temperatures for June would be more revealing as to the region where the heat was most concentrated. Figure 4B shows the departure of highest temperature observed June 9–13, 1956 from the monthly normal maximum for June at each station. This chart indicates very clearly that the greatest departures were in the northern tier of States extending from Idaho to Michigan, with another axis appearing to extend northeastward from Yuma, Ariz. Greatest anomalies, with temperatures of 25° F. or more above the monthly normal maxima occurred in South Dakota, west-

TABLE 2.—*First order stations reporting record temperatures from the northern Great Lakes westward, June 9–14, inclusive*

Station	June						
	8	9	10	11	12	13	14
Cheyenne, Wyo	H	------	------	E	H	H	------
Casper, Wyo	H	H	H	H	H	H	------
Duluth, Minn	------	H	H	------	H	------	------
Sioux Falls, S. Dak	------	H	------	H	H	H	------
Huron, S. Dak	------	H	------	------	H	H	H
Billings, Mont	------	H	H	------	------	------	------
Salt Lake City, Utah	------	H	H	------	------	------	------
Mobile, Ala	------	H	------	------	------	------	------
Madison, Wis	------	H	H	H	H	H	------
Helena, Mont	------	------	H	------	------	------	------
Regina, Sask	------	------	R	------	------	------	------
East Lansing, Mich	------	------	------	H	H	H	------
Pueblo, Colo	------	------	------	H	E	E	E
International Falls, Minn	------	------	------	A	------	------	------
Muskegon, Mich	------	------	------	H	------	------	------
Marquette, Mich	------	------	------	------	H	H	------
Escanaba, Mich	------	------	------	------	H	------	------
Milwaukee, Wis	------	------	------	------	H	H	------
Chicago, Ill	------	------	------	------	H	H	------
Toledo, Ohio	------	------	------	------	H	H	H
Kapuskasing, Ont	------	------	------	------	A*	------	------

H=Highest for date.
E=Equalled highest for date.
A=Absolute highest for the station.
R=Record for month.
*Apparent from available data.

ern North Dakota, a large portion of south central Canada, northeastern Minnesota, and Upper Michigan.

The high temperatures reported during the period June 9–13, 1956, aided materially in making this June one of the warmest on record at many of the stations over the eastern half of the Intermountain region, the north central and northern Plains region, the Upper Mississippi River Valley and the upper Great Lakes region. Your attention is called to table 1 in the preceding article by Green [9] which provides a summarization of these temperatures for the month of June.

Table 2 has been compiled from Local Climatological Data for June to indicate stations within the area that reported temperatures which equalled or exceeded the daily maximum during the period selected. The absolute maximum temperature at International Falls, Minn. was exceeded by one degree when a reading of 98° F. was reported on June 11.

9. CONCLUSION

It might be well to state that while it is practically essential that the 700-mb. and 500-mb. height be above normal for the formation of a heat wave condition, this fact by itself is not sufficient in the development of an above normal temperature area.

An excellent example of a large positive 500-mb. height departure and 1,000–500-mb. thickness departure from normal associated with low surface temperatures occurred this June over northern Canada with the central area of departures in the vicinity of 74° N. and 95° W. In this region the positive anomaly values exceeded 1,000 ft. for short periods but generally the anomaly ranged from 600 ft. to over 1,000 ft. above normal from June 20 to June 30 inclusive for the 500-mb. height and the 1,000–500-mb. thickness. However, during this entire period the afternoon maxima ranged from the upper thirties to the middle fifties. That the afternoon temperatures should remain so low during these conditions was due to the cold water in the surrounding area that kept the lower lapse rate stable. The temperature average for the month of June in this Canadian area was below normal.

Furthermore during heat waves these conditions also should be present over a large area. There should be uniformity in the height and thickness anomalies of the various levels indicating a nearly normal and flat surface pressure area. The air mass must approach the dry-adiabatic lapse rate and not be of a stable air mass type. Little or no moisture should be indicated by the upper-air soundings as the sky must be practically cloudless. In addition there should be a high probability of these conditions being or becoming stagnant over the area.

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